

Planning and Operations for Superior Solar Conjunctions during the MESSENGER Mission

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Abstract— Solar conjunctions pose many challenges to the planning and operation of the MESSENGER mission to Mercury. A solar conjunction occurs when the spacecraft and the Sun appear near to each other in the celestial sky relative to Earth-based antennas, within 3° of each other from the point of view of project planning. The conjunction can be a superior solar conjunction, during which the spacecraft is on the far side of the Sun relative to Earth, or an inferior solar conjunction, during which the spacecraft is between Earth and the Sun. Experience has shown that special planning and operations are not required for the inferior solar conjunctions. Superior solar conjunction durations have ranged from 48 days when MESSENGER was still far from the Sun to only three days, depending on the phasing relative to Earth. During superior conjunction periods, both uplink and downlink communication with the spacecraft can be degraded and communications are often deemed unreliable because of interference from solar plasma and scintillation. Superior conjunctions are therefore actively managed during both the cruise and orbital phases of the mission. The MESSENGER operations team has developed a flight-proven suite of activities to mitigate the impact of superior solar conjunctions. These include prudent command-load boundary placement, temporary extension of the command-loss timers, active momentum management techniques, shutting off unnecessary power loads including instruments, special management of the solid-state recorder and command volume, and modification of Deep Space Network track coverage.

Ranging (MESSENGER) mission, since Mercury's orbit resides exclusively within the Earth's orbit. A conjunction occurs when two celestial bodies appear near each other in the sky relative to a third-party observer. A superior solar conjunction refers to the passage of one body on the far side of the Sun relative to the observer, and an inferior solar conjunction refers to the passage of one body between the Sun and the observer. The arbitrary threshold for a solar conjunction from the point of view of MESSENGER project planning occurs when the Sun-Earth-probe (SEP) angle, the angular distance between the spacecraft and the Sun viewed by the Deep Space Network (DSN) antennas, is 3° or less. When the spacecraft and the Sun are in close proximity during a superior solar conjunction, scintillation effects can perturb the radio-frequency (RF) signals sent to and from the spacecraft. These effects can cause the degradation or even complete loss of communication with the spacecraft, depending on the solar dynamics at the time. Further, during both types of conjunctions, noise added to the receiving system from the Sun can increase the noise floor and thus degrade the signal-to-noise ratio (SNR). Special configurations and accommodations must be made in advance of a solar conjunction to ensure spacecraft health and prevent potential science loss throughout the event, given the unreliable and unpredictable quality and stability of the communications. Even the placement of some trajectory-correction maneuvers (TCMs) was influenced by proximity to solar conjunctions. Through careful planning enhanced with experience from a 6.6-year cruise phase, the MESSENGER mission operations team has developed a comprehensive plan for preparing the spacecraft for solar conjunctions and updated those procedures for the special challenges of the orbital phase of the mission.

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1. INTRODUCTION

Solar conjunctions are a necessary component and ongoing challenge to the planning and operations of the **M**ercury **S**urface, **S**pace **E**nvironment, **G**eochemistry, and

2. SUPERIOR SOLAR CONJUNCTIONS

Conjunctions during the Primary Mission

The MESSENGER spacecraft has traversed superior solar conjunctions a dozen times during the primary mission, as shown in Table 1. When MESSENGER was travelling outside the orbit of Venus during the early cruise phase of the mission, two conjunctions were each more than one month long. During Mercury orbital operations, however, conjunctions are typically less than one week in duration. Flight experience has shown that communications with the spacecraft during inferior solar conjunctions are relatively

unaffected. As a result, this paper will focus exclusively on the challenges of operations and planning for superior solar conjunctions.

Table 1. Superior Solar Conjunctions during the MESSENGER Primary Mission

Conjunction	Start Date	End Date	Duration
1	17 Oct 2006	18 Nov 2006	33 days
2	26 Oct 2007	12 Dec 2007	48 days
3	04 Jun 2008	08 Jun 2008	5 days
4	23 Dec 2008	06 Jan 2009	15 days
5	06 Jun 2009	10 Jun 2009	5 days
6	03 Nov 2009	17 Nov 2009	15 days
7	24 Apr 2010	29 Apr 2010	6 days
8	28 Aug 2010	02 Sep 2010	6 days
9	20 Feb 2011	27 Feb 2011	8 days
10	10 Jun 2011	14 Jun 2011	5 days
11	25 Sep 2011	02 Oct 2011	8 days
12	04 Feb 2012	06 Feb 2012	3 days

Communication and Sun-Earth-Probe (SEP) Angle

Communications begin to deteriorate at a 3° SEP angle, but total loss of contact with the spacecraft does not usually occur until the SEP angle drops below 1.5°. However, given the variable and unpredictable nature of communications when operating with such a low SEP angle, flight preparation deadlines are linked to the 3° SEP angle. Figure 1 shows the relative positions of Mercury, Venus, Earth, and the Sun and a depiction of the SEP angles (not to scale) near the middle of the September 2011 superior solar conjunction.

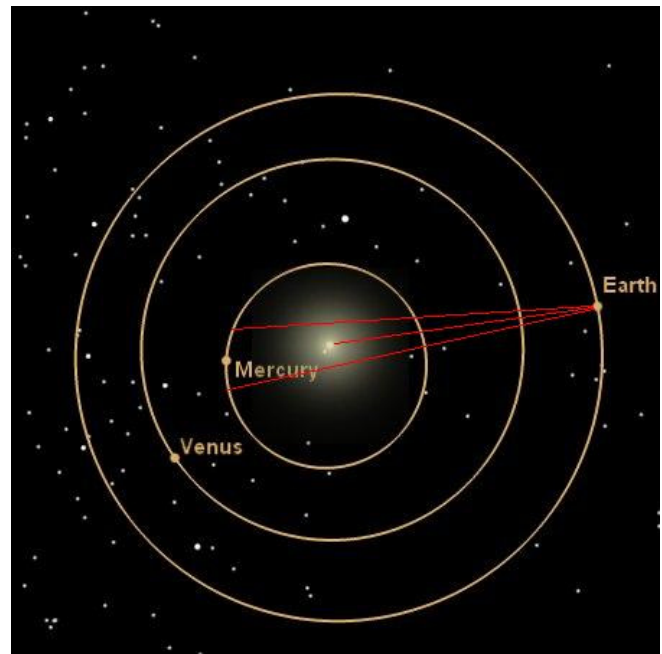


Figure 1 - Planet Positions and SEP depiction during the September 2011 Superior Solar Conjunction

No-Op Burst Tests

The extent of reliable communications was tested during the first two solar conjunctions of the mission to establish a baseline for future reference, given that actual performance over the course of the 6.6 year cruise phase and orbit phase would vary due to the solar cycle. DSN tracks were scheduled deep into the conjunctions, and a series of No-Op (no operation) burst command tests were conducted. Each daily test involved transmission of sets of No-Op commands to the spacecraft to see how many were successfully received by observing an on-board command sequence counter. In tandem with monitoring the quality of the downlink, these tests showed that communications with the MESSENGER spacecraft were still reliable within the 3° limit and generally remained reliable to an SEP angle threshold of about 1.5°. With this information in hand, all future solar conjunctions were plotted with hourly SEP angles to determine when DSN tracks should be scheduled and when flight activities should be completed with sufficient margin. Figure 2 shows the daily variation of the SEP angle during the September 2011 conjunction as a representative example. Due to the length of the first two conjunctions and the limited conjunction experience base of the operations and engineering teams, the full teams gathered at the control center on the first day following the long outages to confirm spacecraft health and safety and to respond to any anomalies that may have occurred during the long outages.

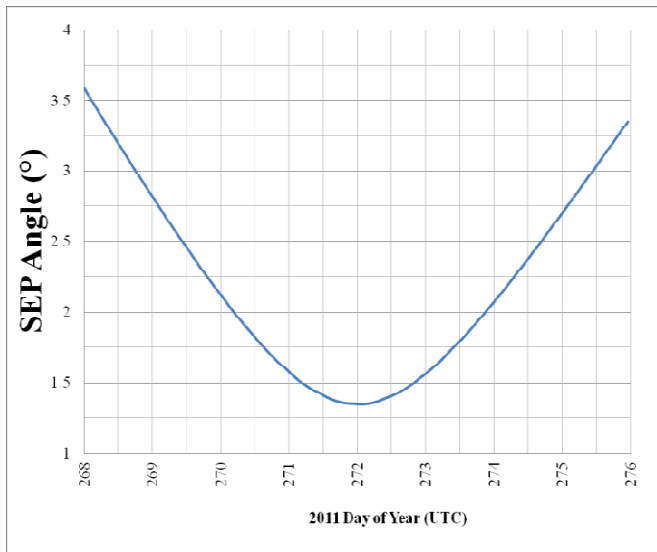


Figure 2 - SEP Angle Variation during the September 2011 Superior Solar Conjunction

3. MITIGATION TECHNIQUES

There are several mitigation techniques that are used to see the MESSENGER spacecraft safely through a superior solar conjunction, thereby preventing potential science loss. These techniques include adjustments to command load boundaries to ensure sufficient uplink opportunities, scaling back of non-essential flight activities, solid-state recorder (SSR) maintenance, tailored DSN track scheduling, on-board command-loss timer adjustment, and downlink/uplink rate reductions to increase the robustness of the communications link. During the cruise phase of the mission, additional mitigations were also implemented. For example, daily attitude alternations were sequenced in which the spacecraft was rotated about one axis and then back again hours later to modify the momentum distribution across the reaction wheels. This non-propulsive momentum control was designed to avoid autonomous momentum dumps while out of contact for long durations. The attitude alternation scheme was combined with strategic solar panel positioning and relative offsets to reduce pinwheel effects. Instrument activities were also curtailed since there was no high-priority science collection and there would be few opportunities to take action should an instrument experience a problem. The science payload was fully powered off during the longer cruise phase conjunctions. Similarly, the oven-controlled crystal oscillator (OCXO) was de-selected for spacecraft timekeeping to eliminate a potential contributor to an on-board problem in the blind. The OCXO was not required in the Cruise phase of the mission and a full demotion sequence would result should it have a problem while selected. The prime science orbital mission places a premium on science collection and data return, but not at the expense of spacecraft health and safety. During the orbital phase, however, the instruments can conduct full observations and the OCXO remains selected, mainly because the time spent at an SEP angle of less than 1.5° is quite short, and daily DSN contacts are scheduled. Payload

conjunction activities are closely reviewed in advance, to ensure that the command load size is not oversubscribed and to avoid saturation of the SSR. In cruise and orbital operations, the mission planners adjust the length and content of command loads to span the duration of a conjunction period.

4. COMMAND LOADS

The MESSENGER mission planners generate command loads to execute weekly activities on the spacecraft. During the cruise phase of the mission, the typical command load spanned two or even three weeks due to the relatively sparse volume of activities and only three DSN tracks per week. In the orbital phase, because of the much larger command volume demands and daily tracks, the command loads are one week long, and those loads are in turn split into two parts. Each part can take up to three or even four hours to load, depending on the Earth distance and other factors such as specific instrument operations.

Command-Load Boundary Placement

Typically, orbital phase command loads run from Monday to Monday for a consistent Near-Term Science Plan schedule. However, when conjunctions are present, the Monday and mid-week command-load boundaries are reassessed, because the unreliability of the uplink during a conjunction window can make the successful uplink of a command load segment impossible. Command loads are constructed as one large binary file and uplinked as a series of uplink transfer frames, often several hundred in total. If even one of these frames is dropped, then the entire command-load attempt is aborted and has to be restarted from the beginning. A command lockout condition, in which the spacecraft will not attempt to process any additional commands after 64 consecutive commands are rejected, can occur if the dropped frame is greater than 64 frames from the end of the load. A lockout condition requires additional restoration steps to be conducted prior to restarting the command load uplink. When the tracks typically reserved for sending a command load are expected to be unreliable for uplink, the command-load boundaries must then be altered. Command-load boundaries are chosen so that a new command load begins just as the spacecraft is about to cross the 3° threshold for a conjunction. This timing gives the operations team multiple opportunities to uplink the command load prior to a conjunction, as well as time to monitor the transition to the new load before communication with the spacecraft is significantly degraded. This strategy also provides sufficient reliable communications above the 1.5° SEP angle so that emergency action can be taken if needed. The command load is also extended on the back end so that it covers the entirety of the conjunction, plus two additional DSN days. This procedure ensures that there is sufficient uplink opportunity for the next command load before the conjunction command load expires, thereby continuing the desired daisy-chain transition scheme.

Command Density and Activity Placement

During the orbital phase, the split command loads are often condensed into one command load that lasts the full duration of the conjunction, depending on the specifics of the SEP range. Close coordination with the science planning team is required to ensure sufficient time to scale back activities if necessary so that the command volume for an entire week will fit into the macro and time-tag memory space of one command load segment. The September 2011 command load did not require any scaled-back payload commanding after analysis of early test builds of the sequence, and careful management of housekeeping commands enabled that sequence to be built as one piece. During the cruise phase conjunctions, many tracks often fell within the window when the SEP angle was less than 1.5° . As a result, these DSN tracks were typically canceled outright because there would be little chance of communication, but also as a courtesy to other DSN users. The attitude alternation schemes were also simplified in these periods since Earth pointing did not interrupt the plan. During the orbital phase, daily DSN tracks are part of the nominal baseline scheduling plan, and they are left intact since the duration when the SEP angle is less than 1.5° is short. Retaining daily tracks does not preclude changes to flight activities, however. Good examples are the weekly commanded momentum dumps (CMDs), typically scheduled for Tuesday tracks. A CMD uses the propulsion system to reduce stored momentum from the reaction wheels since attitude alternations are not practical in the prime science orbit phase. Since telemetry downlink is unreliable during conjunctions, the momentum dumps are removed from the conjunction loads to reduce the chance of a problem while out of contact. In some cases the CMDs can be skipped as long as momentum will not reach the parameterized threshold for an autonomous momentum dump prior to the next CMD opportunity after the conjunction. Other times, the CMD is simply moved from the standard day to an earlier day prior to the conjunction. For the September 2011 conjunction, the operations team performed a CMD on the previous Friday in order to skip the conjunction week altogether. During the cruise phase, attitude alternations were sequenced to avoid momentum accumulation above the threshold for an autonomous propulsive momentum dump maneuver while out of contact.

5. SOLID-STATE RECORDER MANAGEMENT

Another consideration prior to entering conjunctions is management of the solid-state recorder (SSR) and corresponding DSN scheduling. MESSENGER has a large file storage system with a 1 GB capacity. Prioritized files are played back automatically during the daily tracks. Often the playback system can downlink all of the stored files on board, but when downlink rates are lower, all of the files cannot be played back each day, and they begin to accumulate.

Avoiding SSR Saturation

During solar conjunctions, SSR playback is sequenced only to the 3° SEP angle threshold. However, during real-time operations manual playbacks are conducted once good communications are confirmed at the start of each DSN track that is within the 1.5° to 3° range, as long as the downlink rate is above 1600 bits per second (the minimum for SSR playbacks on MESSENGER). An additional strategy that has been employed to reduce SSR data accumulation is to alter an onboard file filter table (FFT). The FFT controls the sampling of individual packet routing to the recorder files. As an example, a telemetry packet could be reduced from a sampling of once per second to once every ten seconds, as long as after-the-fact health and safety trending is not compromised. A related mitigation effort was the development of onboard autonomy to open a new dedicated recorder file once per day in the event of a spacecraft demotion, since command loads are suspended following a demotion. This step was a prudent measure given the two long conjunctions of 2006 and 2007 to avoid potential SSR saturation or at least creation of very large downlink packet files.

SSR File Playback and DSN Scheduling

To ensure that the SSR has as much free space as possible heading into a conjunction, the operations manager often schedules several tracks using the DSN 70-m antennas in the days prior to and following the longer conjunctions. These 70-m tracks can support downlink rates approximately four times higher than the typical 34-m tracks, enabling a much higher volume of files to be played back to the ground and removed from the recorder. Entering conjunction with as much free space on the recorder as possible allows for more files to accumulate during the conjunction, thereby minimizing the potential need to reduce science activities. In addition to clearing out the recorder, another desired step prior to conjunction is ensuring that there are no active playback transactions at the conclusion of the final pre-conjunction playback. Any file transactions left in an open state could time out and be abandoned during the conjunction, requiring later clean-up and therefore wasted time and bandwidth for science return. To avoid such an event, playback is halted earlier than normal during the final track prior to conjunction, open transactions are manually canceled, and the files then cleanly transition back to their original memory locations for future downlink. The post-conjunction 70-m tracks are also desirable because contingency engineering data that are often auto-deleted onboard the spacecraft unless there is a known anomaly are often played back deliberately after a conjunction to confirm that nothing unusual occurred during the communications outage period.

6. COMMAND LOSS TIMER ADJUSTMENT

The MESSENGER flight software has a common protection feature known as a command loss timer (CLT) actively running on the two fault protection processors (FPPs) that

monitor spacecraft health and safety and execute the onboard autonomy. The CLT is a timer that counts down toward zero until a specific command is sent to the spacecraft to reset the timer back to the starting value. The CLT acts as a failsafe in case the spacecraft experiences a hardware or pointing anomaly that renders it unable to accept commands. Should this timer ever reach zero, the FPP will abort the command load, power off the payload, and demote the spacecraft into a known, Sun-safe rotisserie state known as Earth acquisition mode. The idea of intentionally riding out long solar conjunctions in the Earth acquisition mode was studied and considered for the Cruise phase, but would not be practical in the orbital phase given the negative science impacts. Such an outcome actually happened in 2006 because of a spontaneous main processor reset that occurred in close proximity to the long conjunction outage period, culminating in the only autonomous momentum dump of the mission to date (since the scheduled command sequence was no longer running). The commands to reset the CLT are informally known as “tickle timer” commands. In the cruise phase, the CLT was nominally set to 7 days. In orbit, the CLT is set to a default of 5 days given daily DSN contacts. During each DSN track, the tickle timer command is sent to reset the timer to the default value. Since commanding is unreliable during conjunction tracks, the CLT timers must be extended to avoid a potential spacecraft demotion. The new, wider CLT is established about two days prior to a conjunction and is set sufficiently long to extend two days past the 3° SEP angle threshold. If good commanding is confirmed on the back end prior to that date, the CLT can be restored to the default early. During short conjunctions, the timers are set to the new value only in random-access memory (RAM). However, during longer conjunctions the wide CLT is also required in electronically erasable programmable read-only memory (EEPROM). EEPROM is the source from which RAM will draw all the settings and configurations in case of a spontaneous processor reset. The default FPP EEPROM CLT value is sufficient for normal operations and short conjunctions in the unlikely event of a spontaneous reset. But the EEPROM CLT has to be widened for conjunctions that exceed this duration as a precaution.

7. COMMUNICATION OPTIMIZATION

There are additional planning steps that are often taken in an attempt to increase the odds of establishing communication within a conjunction for health and safety monitoring.

Downlink Bit Rate

For tracks during which the SEP angle is less than 2°, the downlink bit rate is minimized to enable the DSN antenna to use a greater bandwidth to attempt to lock the symbol loop and the turbo decoder to establish telemetry lock. For example, a downlink rate of 800 bits per second is sufficient for obtaining real-time updates of all the packets in the default real-time list, so that rate was chosen for the week of the September 2011 conjunction. In normal operations, 800 bps are reserved for real-time telemetry by default, and the

remainder of the downlink margin, usually many thousands of bits per second, is used for playback of SSR files. Lowering the downlink rate gives the antenna extra margin to lock onto the signal despite solar interference or higher temperatures on the Sun-facing antennas, and increases the odds of receiving telemetry frames.

Disabling Ranging

Extra margin on the uplink can be gained by disabling ranging during conjunction passes. Ranging involves a series of tones sent to the spacecraft and returned, which are then used to determine the spacecraft’s range in relation to the Earth since all of the timing delays in the path are known. With ranging disabled, the full transmitter power at the DSN antenna is applied to commanding and carrier tracking, making the signal stronger and more likely to reach the spacecraft successfully, and the downlink is similarly limited to just modulated real-time telemetry.

Aberration Attenuation

One additional downside to commanding during these conjunction periods is aberration attenuation. Since the spacecraft is moving primarily laterally to the line of sight from Earth during conjunction periods, commanding can be further compromised because DSN antenna pointing is optimized for downlink on MESSENGER rather than uplink. This effect is even more pronounced when using the 70-m antennas and their corresponding narrow beam widths. This situation underscores the need to provide ample command opportunities and margin when voluminous commanding is required in or even near solar conjunction periods.

8. SPECIAL PLANNING AND SCHEDULING

Conjunctions in Proximity to Mission Milestones

Special navigation planning and scheduling considerations are taken into account when a superior solar conjunction occurs near a planned mission milestone, such as a major deep-space maneuver (DSM) or a trajectory-correction maneuver (TCM), as well as the selection of the data cutoff time for weekly orbital phase orbit determination (OD) deliveries. The timing of a TCM or a contingency TCM opportunity is altered if the conjunction location causes disruption to the maneuver planning or execution, or if there are post-maneuver time constraints such as preparing for a clean-up maneuver or upcoming planetary flyby. Unfortunately, this movement often results in a non-optimal date in terms of either expenditure of spacecraft velocity change (ΔV) or burn attitude in order to remain within other constraints such as enforced spacecraft tilt relative to the Sun. Conducting a maneuver optimally but out of contact during a conjunction is considered too high a risk. The maneuver execution time itself is not the only factor to consider; it is also important to ensure that the navigation team has sufficient orbit determination or reconstruction data collection periods before and after the maneuvers while maintaining time needed for other communication-

dependent activities.

Data Collection Opportunities prior to a Milestone

Prior to a maneuver or planetary flyby, the mission planning and navigation teams must have precise measurements of the spacecraft's position and velocity. This information is obtained through routine Doppler tracking and ranging during standard DSN tracks and, in the cruise phase, through specialized data collected in a series of activities called Delta Differential One-way Ranging (DDOR) tracks. DDOR tracks involve DSN antennas at two different complexes alternating between locking onto MESSENGER and onto a known fixed quasar from a table of choices within a few degrees of the spacecraft's position. When the spacecraft was near a conjunction during the cruise phase, daily tracks rather than the more typical four tracks a week were scheduled to ensure better maneuver design or reconstruction coverage for navigation. In addition, maneuver dates sometimes had to be adjusted in order to allow sufficient overall DSN track time and DDOR opportunities on either the front or back end of the maneuver depending on the timing of the conjunction. For example, DSM-2 was conducted on 17 October 2007 and the second superior solar conjunction began soon thereafter on 26 October 2007. The clean-up maneuver after DSM-2 was TCM-19, which had to be placed non-optimally on 19 December 2007 rather than on 30 October because of the location of the long solar conjunction.

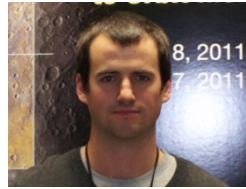
9. SUMMARY

The mission operations team has developed and utilized a diverse set of mitigation techniques to see the MESSENGER spacecraft safely through twelve superior solar conjunctions to date, given that normal communications cannot be counted on during these times. Experience has yielded insight and confidence in the reliability of uplink and downlink as a function of time through the conjunctions and shaped how the mission planners schedule and configure DSN tracks and command load sequences accordingly. With dense biweekly command loads and primary science data collection, the orbital phase of the mission required a modified approach to conjunction management to ensure prime science data return, even though the durations are generally shorter overall. Careful placement of load sequence boundaries and critical events that require real-time monitoring relative to actual expected outage periods, combined with early analysis of command volume and SSR peaks for potential modification of science data acquisition plans, are the keys to the orbital phase solar conjunction management. By initiating the planning process months ahead of a conjunction, the operations team is able to smoothly and safely account for all of the difficulties that a conjunction presents, since each one is unique in terms of duration, SEP angle range, and location within a calendar period. The approach of the MESSENGER team to superior solar conjunctions allows for a continuation of as much of the planned science as possible while ensuring that the spacecraft remains in a healthy and risk-free state, and

therefore serves as a resource and a model for other current and future missions that will encounter similar issues.

BIOGRAPHIES

Donald Mackey received a B.S. in Aerospace Engineering from the University of Maryland in 2006 and an M.S. in Applied Physics from Johns Hopkins University in 2010. He has been with the Johns Hopkins University Applied Physics Laboratory (JHU/APL) since 2006. He has been a member of the MESSENGER team as a flight controller since joining JHU/APL and as the Mission Operations Command and Data Handling analyst since 2008, with a focus on the program's CCSDS File Delivery Protocol system.



Andrew Calloway has over 18 years of experience in spacecraft operations. He graduated from Georgia Tech with a Bachelor of Aerospace Engineering degree and began his space career supporting commercial and international geosynchronous communications satellite launches and operations through the early and mid 1990s. In 1996 he began six years supporting the Tropical Rainfall Measuring Mission, a low-Earth-orbiting Earth resources satellite built and operated at the NASA Goddard Space Flight Center, where he advanced to become the technical operations lead in 1998. He has been a member of the MESSENGER operations team since he joined JHU/APL in 2002, and he has been the Mission Operations Manager since January 2007. MESSENGER launched in August 2004 and traveled through a 6.6 year cruise phase through the inner solar system that included six planetary flybys before Mercury orbit insertion in March 2011.

